Differential-mode Band-pass Filter with Wideband Behaviour Featuring Intrinsic Common-mode Suppression

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***Abstract*— This study introduces a differential-mode band-pass filter (BPF) implemented using microstrip topology, specifically designed for wideband applications. The introduced filter is designed using branch-line configuration, incorporating input and output (I/O) cross-coupling to enhance performance. Notably, the design achieves an exceptional common-mode suppression exceeding 40 dB while maintaining structural simplicity. To validate its effectiveness, this filter is manufactured in-house and experimentally tested. The measurement responses closely align with theoretical predictions, demonstrating strong agreement and confirming the feasibility of the proposed design.**

Keywords- Differential filters; Wideband filters; common-mode suppression; Balanced filters.

I. INTRODUCTION

In contemporary communication systems, band-pass filters (BPFs) are indispensable components due to their compact form factor, high performance, and cost-effective design. There has been an increasing interest in this technology among both academic and industrial researchers since the Federal Communications Commission (FCC) authorized unlicensed ultra-wideband (UWB) systems.

In recent years, balanced or differential-mode microwave filters have garnered significant attention within the microwave research community, driven by the increasing need and utilization for balanced/differential circuitry and systems. Differentially operating balanced-transceivers offer enhanced immunity to many unwanted signals including: noise, crosstalk, as well as electromagnetic interference compared to on the other hand, the single-ended counterparts. In this context, multiple band-pass filters (BPFs) have been proposed, employing various design methodologies to optimize performance.

The study in [1] introduces a band-pass filter with differential-mode operation and highly suppressed common-mode signals; however, its applicability is restricted to narrowband applications. A branch-line-based structure incorporating another methodology implying additional open-circuited stubs is proposed in [2], offering a wideband differential-mode operating passband and an effective common-mode stopband, though at the expense of a relatively large circuit size. In [3], wideband differential band-pass filters (BPFs) utilizing a T-shaped structure are presented, but they exhibit limited suppression of common-mode signals. Different wideband DM BPFs designed for ultra-wideband (UWB) applications is introduced in [4], though it suffers from inadequate frequency selectivity within the passband and common-mode suppression. Additionally, a differential UWB BPF based on the transversal signal-interference concept is reported in [5]; however, its design sensitivity results in suboptimal differential and common-mode performance. While some designs [6] – [9] lack good CM suppression level, other works reported in [10] – [14] introduce complexity.

This paper presents the design and implementation of a wideband differential-mode band-pass filter (BPF) centered at 6.85 GHz, featuring high selectivity, size compactness, and inherent suppression of common-mode signals. The proposed filter is realized using microstrip topology and employs a branch-line configuration with input/output (I/O) cross-coupling, introduced for the first time, to simultaneously enhance both differential-mode and common-mode responses. To validate the design, a prototype is developed and in section 2, while simulated responses are depicted in section3, followed by the conclusion in section 4 validating the concept with simulated and measured results demonstrating strong agreement.

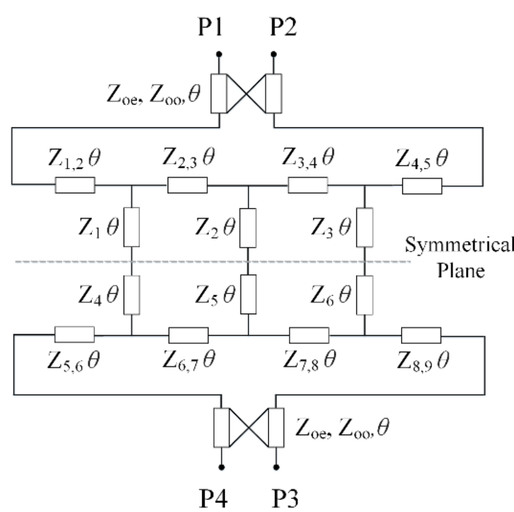

Fig.1. Topology of the proposed wideband BPF.

II. DESIGN

Figure 1 presents the schematic of the proposed design, where Z_i and Z_j respectively denote the stubs of branch-line in addition to the lines for connection. To enhance frequency-

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selectivity and simultaneously optimize the group delay while minimizing the number of resonators, input/output (I/O) cross-coupling is introduced. As observed in Figure 1, the proposed design exhibits perfect symmetry with respect to the central plane (dotted line). Consequently, depending on the type of excitation applied, this plane can be considered a perfect electric or magnetic wall taking into consideration the paired input ports (P1 and P4) and output ports (P2 and P3). Despite comprising only *n* stubs, the design achieves an insertion function of degree *2n-1* in frequency. Circuit parameter calculations can be performed utilizing various design tools known as CAD tools. The optimized parameters of the proposed designed circuit for the wideband differential-mode BPF with I/O cross-coupling are provided in Table I.

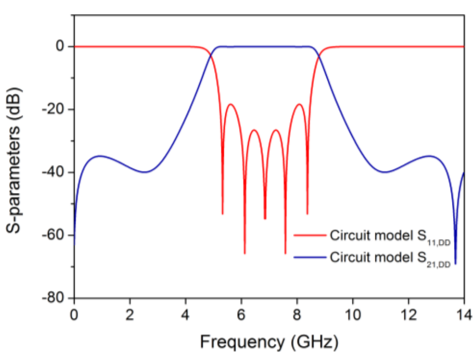
TABLE I
CIRCUIT PARAMETERS FOR DIFFERENTIAL MODE FILTER (θ=90° AT f_0)

Stub line	Connecting line	Coupled line
Z_1=Z_3=Z_4=Z_6= 38Ω	$Z_{1,2}$= $Z_{4,5}$= $Z_{5,6}$= $Z_{8,9}$= 102.1Ω	Z_{oe}= 98.5Ω
Z_2=Z_5= 21Ω	$Z_{2,3}$= $Z_{3,4}$= $Z_{6,7}$= $Z_{7,8}$= 76Ω	Z_{oo}= 79Ω

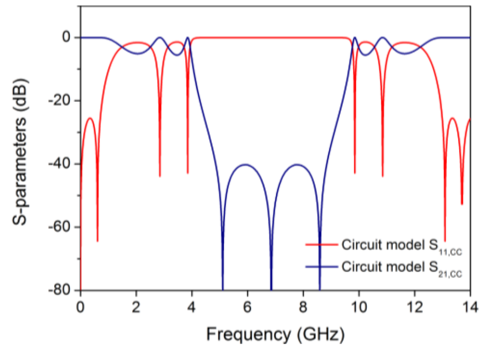
The transmission related to two-port characterization associated with DM and CM for the presented filter is derived from the four-port S-parameters, as expressed by the next methodolgy [6]:

$$S_{11,\,DD} = (S_{11} - S_{41} - S_{14} + S_{44})\ /2 \qquad (1)$$
$$S_{21,\,DD} = (S_{21} - S_{31} - S_{24} + S_{34})\ /2 \qquad (2)$$
$$S_{11,\,CC} = (S_{11} + S_{41} + S_{14} + S_{44})\ /2 \qquad (3)$$
$$S_{21,\,CC} = (S_{21} + S_{31} + S_{24} + S_{34})\ /2 \qquad (4)$$

Figure 2 presents the frequency response of the circuit model, demonstrating the wideband performance of the proposed design with a fractional bandwidth (FBW) of 58%, and centre frequency of 6.85 GHz. As illustrated in Figure 2(a), 5-poles of transmission are obtained *n=3* inside the passband of the DM wideband filter, as anticipated. Furthermore, the bandwidth of the proposed filter can be adjusted and enhanced by optimization of the impedance of even-mode and odd-mode and compromising the differential-mode return loss at the same time. On the other hand, three transmission-zeros for common-mode attenuation are achieved as depicted in Figure 2(b) where two of which are generated by the proposed I/O coupling.



(a)



(b)

Fig.2. Different modes frequency response (circuit model). (a) Differential-mode. (b) Common-mode.

The designed layout of the wideband DM BPF obtained utilizing the electromagnetic simulation as depicted in Fig. 3. The circuit dimensions are: widths: W1=1.3, W2=0.5, W3=0.3, W4=0.7, W5=3.5 and W6=2.0. As for the lengths: L1=2.4, L2=6.7, L3=7.0, L4=7.0 and L5=12.6, (all in millimetres). The presented filter was fabricated using conventional printed circuit board (PCB) manufacturing techniques for microstrip structures. A Rogers RO3003 substrate was employed, characterized by a dielectric constant of 3.0, a loss tangent of 0.0025, and a thickness of 0.5 mm.

III. DISCUSSION

Building upon the aforementioned discussion, a wideband differential-mode band-pass filter (BPF) with center frequency of 6.85 GHz and a fractional bandwidth (FBW) equal to 58% is designed. The prototype was manufactured in-house, and the final measurement results were obtained using an N5225A PNA Microwave Network Analyzer.

Figure 4 presents the simulated frequency responses, plotted for evaluation. Within the intended wide passband, the simulated differential-mode return loss $|S_{11,DD}|$ remains below -12 dB, while the differential-mode insertion loss $|S_{21,DD}|$ does not exceed -1.0 dB, as illustrated in Figure 4(a). Additionally, the simulated common-mode insertion loss $|S_{21,CC}|$ achieves suppression levels better than -40 dB across the entire frequency band of interest.

As evident from the results, there is a strong agreement between the circuit-model and simulated frequency responses. The observed discrepancies between the two can be primarily attributed to EM-environments and tolerances, which introduce losses and impact the structural symmetry of the design. Consequently, these variations influence both the differential-mode and common-mode performance. Furthermore, achieving perfect symmetry in practical implementations remains a significant challenge.

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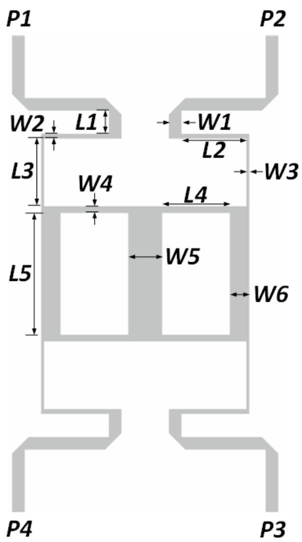
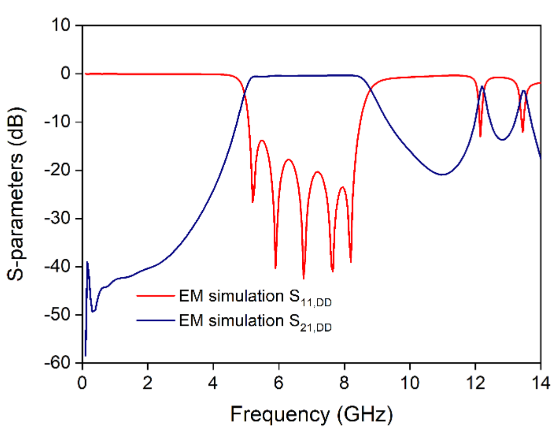


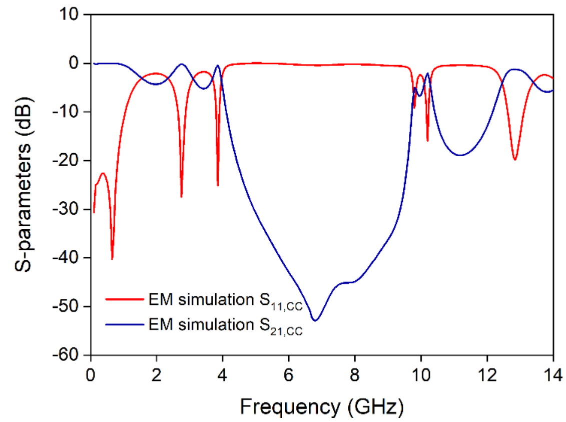
Fig.3. (a) Design layout with relative dimensions.

Figure 5 presents the results of simulation related to group delays of the proposed DM band-pass filter (BPF). The in-band group delays remain consistently flat across the entire passband, indicating stable performance.

A comparison between the proposed design and other wideband BPFs reported in the literature is provided in Table II. The comparison includes key comparison parameters such as the center operating frequency f_0, fractional bandwidth of the differential-mode (DM-FBW), the relative size of circuit in terms of the guided wavelength λ_g^2, and the level of common-mode rejection $|S_{21,\ CC}|$. The proposed wideband differential-mode BPF demonstrates an exceptional common-mode rejection level, exceeding -40 dB across the entire passband. Furthermore, the proposed filter design demonstrates a relatively compact size compared to previously reported designs. Combined with its structural simplicity, these attributes highlight its increasing potential for implementation in communication systems, with special field in ultra-wideband (UWB) technology.



(a)



(b)

Fig.4. EM simulated and measured frequency responses. (a) Differential-mode. (b) Common-mode.

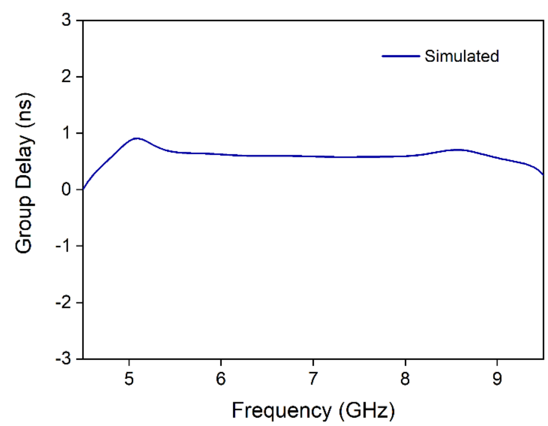


Fig.5. Simulation and measurement group delay.

TABLE II PERFORMANCE COMPARISON WITH OTHER WORKS

Ref.	f_0 (GHz)	DM-FBW (3-dB)	Size (λ_g^2)	In-band $\lvert S_{21,\ CC}\rvert$ (dB)
[3]	6.85	70%	1.1	-14.5
[7]	1.5	43%	0.13	-20
[8]	5.0	22%	0.4	-20
[9]	5.94	61%	0.45	-15.7
[10]	6.8	67.6%	1.38	-15
[11]	5.08	38%	1.27	-17
This work	**6.85**	**58%**	**0.97**	**-40**

IV. CONCLUSION AND FUTURE WORK

This paper presents a wideband balanced band-pass filter (BPF) with inherent common-mode suppression. Using I/O cross-coupling in a branch-line structure, the design enhances both differential and common-mode responses. The design achieves a 58% fractional bandwidth at 6.85 GHz, with common-mode rejection exceeding -40 dB. Circuit-model results closely match with simulations, demonstrating high selectivity and flat group delay. Compared to existing designs, the proposed filter offers superior performance in a compact form, making it well-suited for wideband applications. An interesting approach to improving the performance in the common-mode which is to be later investigated is the implementation of multilayer in approach with particular application of Liquid crystal polymer technology.

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